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POTENTIAL AND RECENT PROBLEMS OF THE POSSIBLE POLYMETALLIC SOURCES IN THE OCEANIC DEPOSITS

Paper presents economical potential on obtaining critical metals from oceanic polymetallic deposits and selected geopolitical problems associated with seafloor partitation. In the group of the most important oceanic metal deposits are: (1) heavy minerals placers, (2) polymetallic nodules, (3) cobalt-rich ferromanganese crusts, (4) seafloor massive sulphides (SMS) and (5) metalliferrous sediments (oozes and clays). Several of them have been considered as the alternative sources of critical metals for high- and green-technology applications. Their occurrence, global distribution, resources and origins are a direct reflection of the geodynamic evolution of the oceans.

The authors also discuss international legal regulations regarding research, prospection, exploration and exploitation of oceanic mineral deposits, including registration of the most promising mining areas by International Seabed Authority in accordance with The United Nations Convention on the Law of the Sea (UNCLOS 1982).

Key words: *polymetallic nodules, cobalt-rich ferromanganese crusts, seafloor massive sulphides SMS, metalliferrous clays, economic geology.*

Economical potential and geopolitical importance of the polymetallic deposits

Wealthy base of mineral resources, being the foundation of Western civilization, was significantly reduced at the turn of the last century. More than ten times increase of the total mineral resources use — up to 33 billion Mg in 2000 — and more than 45 billion Mg in 2010, is limiting further economic development of many countries. Growing political competitiveness and globalization are the main problems affecting the EU, especially due to the European dependence on import of selected raw materials and minerals from Asian and African markets, adversely affecting development of EU companies and possibilities of an effective implementation of the Lisbon Strategy for Growth and Jobs. EU countries are in need to increase security of the supply of scarce raw materials, secure access to the new mineral deposits, prepare rational and efficient methods of the usage of their resources, increase efficiency of exploitation and consumption of critical metals in various industry sectors and also intensive development of new recycling branches (eg. urban mining, use of waste and secondary minerals). Efficient exploitation and development of new the metal sources will significantly extend application range for the new innovative technologies (Kotlinski 2001).

In the last 15 years, most of the stock markets, including metals and other minerals, have been more unstable and susceptible to the sudden price changes. This actions were strongly induced by several changes on the global structure in raw materials supply with increasing demand from developing countries (eg. China, India and Brazil). For example, in China, which is the largest consumer of metals in the world copper consumption increased from 12 to over 40 % — only in the last decade.

Safety of selected raw materials in EU needs to be ensured also due to decrease of the global metallogenic resource potential limiting, as well as supply access and low commodity prices. These conditions refer especially to the rare earth elements (REE) and other «critical» metals, which have the highest economic importance for UE countries (World Bureau of Metal Statistics WBMS 2009; Kotliński 2011).

Effective actions and innovative solutions applied by EU are supposed to reduce metals import dependence and ensure supply security of more than 30 materials (Fig. 1). These tasks are the main priorities of the EU economic program (EU 2013).

Since 2008, the European Commission has been implementing some actions in accordance with Raw Materials Initiative (RMI). The government of Poland has also prepared several legislations settled down in the «Guidelines for the Polish Maritime Policy up to 2020». According to them, the rational use of marine mineral resources should take into consideration the economic criteria and environmental condition of the oceans (Kotliński 2001; Abramowski, Kotliński2011; Mazurkiewicz 2011). Development of legal solutions to enhance raw materials safety and improve efficiency of extraction, recovery and utilization of mineral resources, are essential part of the new EU Framework Program «Horizon 2020», especially in Task 5 entitled «Climate Action, Environment, Resource Efficiency and Raw Materials».

The report of the Günter Verheugen Commission showed that EU countries import most of strategic metals, including: nickel, cobalt, rare earth elements and platinum group elements (PGE). Limited access to these resources is slowing down technological development and production of hybrid engines, electronics, mobile communication, sensors, liquid crystal displays, photovoltaic panels, new types of strong NdFeB magnets used in the wind turbines and others (Hein et al. 2010; Herzig et al. 2000; Abramowski, Kotliński 2011; Kotliński 2011; Hein et al. 2013).

Recent EU challenges are particularly important and undertaken by several integrated programs including RMI Raw Material Initiative, an innovative program of Strategic Research Agenda (SRA) or research programs under the auspices of the International Seabed Authority (ISA). All of them are aimed at diversification and access to new groups of strategic metal resources. For example, current research carried out by ISA is aimed at rational «exploration, prospection and exploitation» (EPE) of polymetallic deposits in the «Open Seas», in full accordance with the «United Nations Convention on the Law of the Sea» (UNCLOS 1982).

Increasing role of some metals in the global economy is evidenced by their growing export rate. In case of Fe deposits export exceeds 40 %, Cu and Zn more than 30 %, Pb about 18 % and Sn up to 80 %. Similar, the highest net consumption is noted also in Fe resources (3 > billion Mg per year), bauxite — more than 20 million Mg/y, Cu — >19 million Mg/y, Mn and Zn — about 7 million Mg/y, Cr — ca 3 million Mg/y. For example, the annual copper production in 2013 equaled 19,9 million Mg (2.3 % higher than in the 2012). Some deposits have been

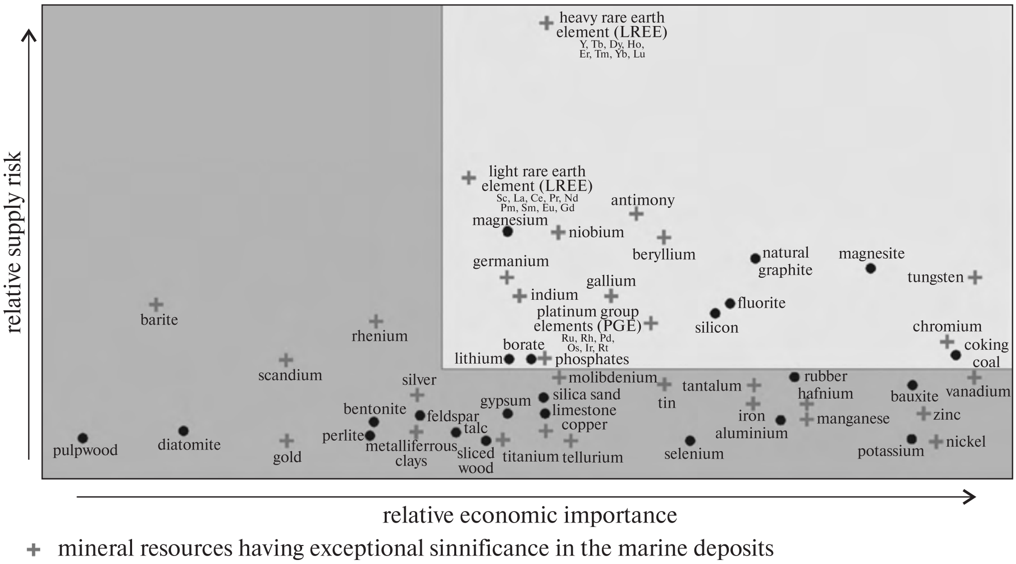

Fig. 1. Strategic resources for the EU mineral politics. Source: Study on Critical Raw Materials at EU Level Final Report (DRAFT) — A report for DG Enterprise and Industry. Access: 9.2013; modified

overexploited, especially: Fe and Cr, bauxite, Cu, Ni, Zn and Au (Krivcov 2000; Lenoble 2000; Crowson 2008; Kotlinski 2011; A. Piestrzyński personal info October 2014).

High industry usage of strategic metals is stated by gradual increase of the total industrial metal requirement rates: Zn (3.81), Co (3.42), Ni (2.19), Cu (1.86), Sb (1.72), Sn (1.45), Pb (1.32), Mn (1.14), Au (1.15) and less than one for Cr and Ag. Regardless of the reliability of the forecast period, it becomes obvious that after 2020 some important raw materials will be much more difficult to access.

Polymetallic deposits of the oceans are considered an important potential source of strategic minerals, including ferrous and non-ferrous metals, REE's and PGE's. Special industrial value in this group have sulphide and oxide mineral deposits showing high enrichment in Ni, Cu, Co, Ag, Au, Mn, Mo, Zn, PGE and REE. It should be strongly emphasized that metal concentrations in the oceanic deposits (especially Ni, Co, Cu, Ag) compared to land sources are similar (Abramowski, Kotliński 2011; Kotliński 2011; Szamałek, Mizerski 2011; Piestrzyński 2011; Zawadzki 2013).

The main factors affecting on the exceptional economic value of polymetallic ocean deposits are: 1) significant presence of strategic metals; 2) metal concentration usually higher in comparison to the land deposits; 3) great total prognostic resources.

Oceanic deposits are often characterized by better technological parameters of mineral output. In terms of economic value, they are comparable to the richest sulphide Cu-Ni ores (for example Norilsk type). Only in polymetallic nodules, the average metal content is higher than in the land sources: Ni — 1.1; Cu — 1.14 and Mn — 1.3. Cobalt amount in Co-rich manganese crusts is more than 5 times higher. Excluding the main metals, the following are also of practical importance: Mo, Au, Ag, Zn, PGE, REE (mainly Ce, Nd, Y, La), Ti, W, Zr and Bi (Halbach et al., 1984; Kotliński et al. 1997; Cronan 2000; A Geological Model of Polymetallic Nodule Deposits in the Clarion-Clipperton Fracture Zone 2010; Abramowski, Kotliński 2011; Kotliński 2011; Piestrzynski 2011).

Polymetallic deposits of the oceans

Crude oil and natural gas, heavy minerals and gemstones, construction materials, chemicals, phosphates and other resources, according to the UNCLOS Convention, are located within the «Exclusive Economic Zones» (EEZ) and «Continental Shelf» — areas under the jurisdiction of coastal states. The largest polymetallic deposits were allocated in the «Open Seas», so in the legal terms they are under international jurisdiction of ISA. Widely known and exploited EEZ's placers deposits of heavy minerals (mainly magnetite, titanomagnetite, ilmenite, rutile, zircon, monazite, cassiterite, chromite, gold and platinum), which are the sources of Fe, Ti, Ce, Zr, Sn, Cr, W, REE, Au, Pt and Ag, have similar metallogenic potential like deep sea sulphide and oxide Fe-Mn resources (polymetallic nodules, cobalt-rich ferromanganese crusts, seafloor massive sulphides; metalliferrous oozes/clays), corresponding to the SEDEX hydrothermal type. They possess, in general, higher concentrations of Mn, Cu, Ni, Co, Zn, Pb, Mo, V, Ti, Ag, Au, Pt, REEs and PGEs. They occur in extremely different geological-mining conditions, distinguished by great depth extension, variable technological parameters and exploitation requirements, different ore physical states, changes in chemical and mineralogical composition of the mineral output and often great differences in the metals concentration. Most of the geological research, based on distinguished types of the oceanic polymetallic deposits, confirmed high regional variability in the metals content (Fig. 2, see color plate) (Shnyukov et al. 1979; Kotliński, Szamałek 1998; Mizerski, Szamałek 2009).

Research has shown that about 80 % of total estimated potential metal resources occur in the Pacific and significantly less within the Atlantic and Indian Ocean (Fig. 2, see color plate). Compared to land deposits, the total ocean resources are 57 times higher for manganese, 87 times for nickel and 359 times for cobalt (ISA; access October 2013).

Polymetallic nodules

Polymetallic nodules cover vast area of the seafloor. The most prospective fields are located within abyssal basins at water depths of 3500—5500 m (Fig. 2) (Shnyukov et al. 1979; Shnyukov 1981; Kotlinski, Szamanek 1998; Andreev, Gramberg 2000; Hein, Koschinsky 2013). Among them, the unique Clarion-Clipperton field located in the tropical Eastern Pacific region and the Central Indian Ocean Basin is of the greatest economic potential (Fig. 2) (Hein 2006; Kotliński 2011; Abramowski, Kotliński 2011).

Polymetallic nodules are buried in the semi-liquid sediment cover (active layer), mainly siliceous-clayey silts, showing weak physical and mechanical properties. Nodules are fragile, often fractured, with varying morphology. They can be also locally buried. Their accumulation state on the seafloor is geologically estimated as a density ratio (the amount of nodules in kg/m^2) showing some variability depending on the seafloor relief (Kotliński, Stoyanova 2006).

Recognized spatial distribution accuracy of the polymetallic nodules is directly related to their mixed hydrogenic-diagenetic formation. Main processes are the following: precipitation of colloidal Fe-Mn aggregates, sorption of metals from bottom/pore waters and diagenetic metal remobilization. The complex mechanisms of nodules formation are strictly subordinated to the inteval of the carbonate compensation depth (CCD).

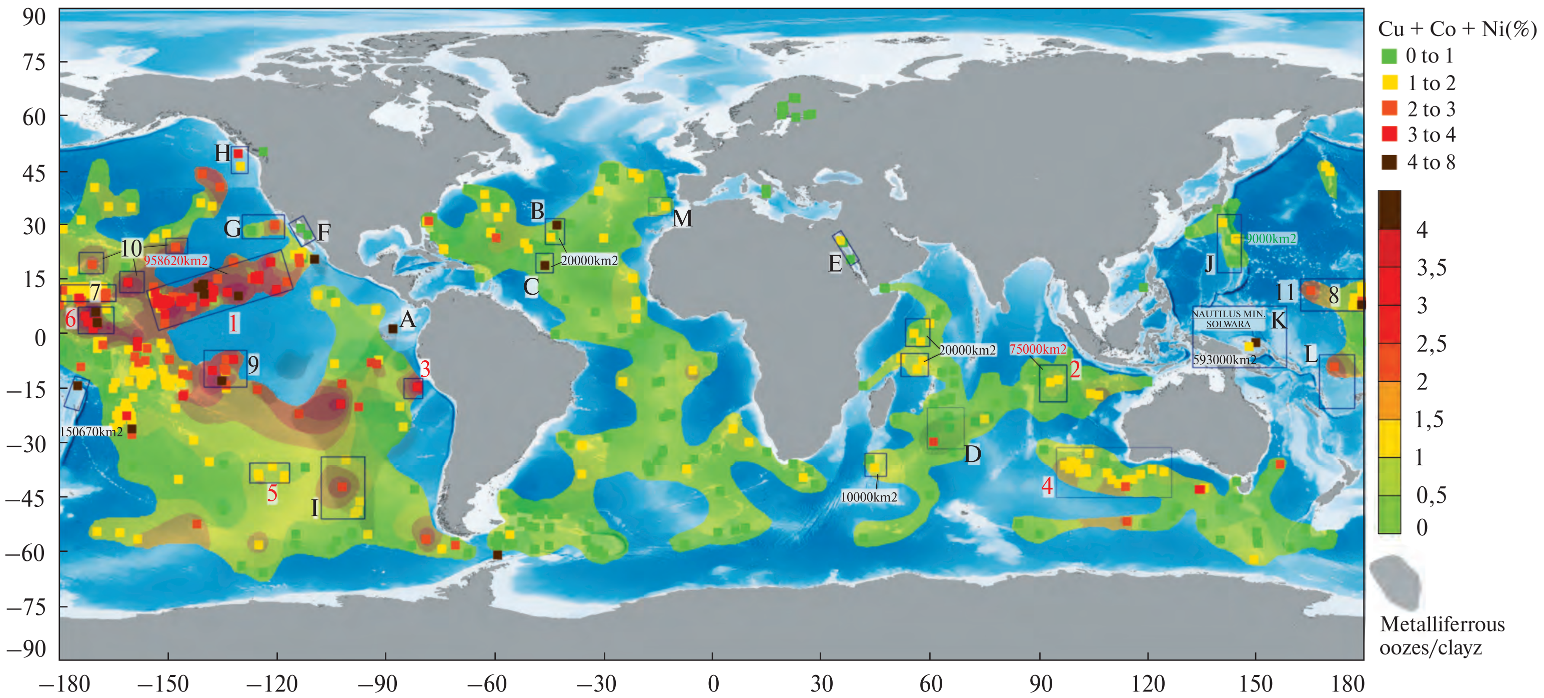

Fig. 2. Simplified metallogenic potential map of oceanic polymetallic resources. Compiled basing on: 1) Imagery by Jesse Allen, NASA's Earth Observatory, using data from the General Bathymetric Chart of the Oceans (GEBCO) produced by the British Oceanographic Data Centre; 2) ISA seafloor crust/polymetallic nodules chemical composition database (access 03.2015); 3) US University of Szczecin, Marine Geology Unit archival data base (03.2015); 4) Herzig et al. 2000; 5) Mizerski, Szamalek 2009; 6) Gurvich 2006; 7) Zawadzki 2013. Polymetallic nodules:1) Clarion-Ciperton Facture Zone (CCFZ); 2) Mid-Indian Ocean Basin; 3) Peru Basin; 4) Diamantina field; 5) Menard field; 6) Mid-Pacyfic Basin. Co-rich crusts: 7) Wake-Necker Ridge; 8) Marshall Seamounts — Magellan Rise; 9) Tuamotu Fracture Zone (TFZ); 10) Johnston — Line — Hawaii islands; 11) Federated States of Micronesia and Palau; Papua-New Guinea. Seafloor massive sulfides SMS: A) Galapagos ridge; B) hydrothermal fields Tag, Broken Spur, Lucky Strike, Rainbow and Menez Gwen; C) hydrothermal fields Snake Pit, Puy des Folles, Zenith-Wiktorija, Logatchev, Siemionov, Aschadze and Krasnov; D) hydrothermal fields Sonne, Meso and Mt. Jordanne; E) Red Sea depths; F) Guaymas basin; G) Escabana basin; H) Explorer ridge; I) East Pacific Ridge EPR; J) Marian trench and Izu-Ogasawara basin; K) Manus basin; L) North Fiji and Lau basins; M) Azores

Fig. 3. Genetic types of the polymetallic nodules from CCFZ (photo by courtesy of IOM)

In case of CCFZ it is approximately 4400 m below sea level (Kotliński, Szamałek 1998; Kotliński, Stoyanova 2006; Yubko, Kotliński 2009; Kotliński 2011; Maciąg et al. 2011).

At CCD the water depth of 4200 m dominate small (<4 cm) spheroidal «H» type nodules, showing smooth surfaces, high Fe (10,32 %) and Cu (0,23 %) content, and relatively lower amount of Mn, Ni and Co. At the 4200—4400 m bsl, the transitional «HD» type occurrs, distinguished by Mn >30,5 % increase, smaller amount of Ni-Cu and less than 0,18 % Co. Discoidal and ellipsoidal diagenetic «D» nodules are larger (6—12 cm), with botryoidal surface (Fig. 3). They occur generally below CCD — usually deeper than 4500 m bsl.

Research in the CCFZ shown that the amount of «H» and «HD» type decreases (mode sizes <6 cm), with simultaneous gradual increase of «D» type (the size of modal> 6 cm). It is mainly due to seafloor rotation and descent from N to S. Genetic types of the polymetallic nodules from CCFZ have been shown on the Fig. 3.

Spatial polymetallic nodules genetic types distribution and metal concentrations are determined by mineral composition changes, which impacts on potential industrial ore quality. Vernadite (δMnO_2) is dominating amorphous mineral phase in the «H» type polymetallic nodules. However, more of «D» type crystalline phases, such as todorokite (10 Å) and birnessite (7 Å) have also been confirmed. With depth raising from N to S (15—9°N), strong geochemical pattern is visible: increase of Mn and Cu — decrease of Ni and Co content. High cobalt concentrations are typical for «H» and «D» polymetallic nodules type, occurring mainly in the northern part of the CCFZ. The «D» type nodules from central and south CCFZ are significantly enriched in Mn, Cu and Ni (Kotliński, Szamałek 1998; Kotliński 1999; Kotliński et al. 2009; Kotliński 2011).

Contours of the productive ore zones and their isolated sizes/forms are strongly determined by the seafloor relief of the CCFZ. The borders of the «streaked» fields with width ranging from 2 to 10 km and length of several dozen kilometers, are determined by geological nature of several seafloor elevations/depressions, usually with inclined slopes. The «patchy» (flat seafloor) ore fields have greater width of about 70 km and a length often over 120 km. Both types of ore fields are showing high variation in size and polymetallic nodules distribution.

The great value and potential of polymetallic nodules is not only the result of the ore quality. They are considered as an effective sorbent used for gas purification and as a raw material for inorganic ion exchange materials synthesis. Some derived products may replace expensive synthetic bitumens used to water deactivation, special materials applied in the industrial waste purification and into metal recovery (Abramowski, Kotliński 2011; Kotliński 2011; Zawadzki, Kotliński 2011; Zawadzki 2013).

Cobalt-rich ferromanganese crusts

The largest revealed deposits of the ferromanganese crusts enriched in Mn, Co and Pt, were found on the conical seamounts and guyots in the northern part of Lain volcanic chain, Marshall Islands, an Tuamoto archipelago, in Wake-Necker area in the Pacific and on the Rio Grande plateau in the Atlantic Ocean (Fig. 2). Crust resources in the Pacific Crust Zone (PCZ) were estimated on about 7.5 billion Mg. PCZ includes central and western equatorial Pacific, from 20°N latitudes: EEZ Johnston Islands, Wake, part of Hawaii (USA) and Marshall Islands (Hein 2006; Hein, Koschinsky 2013).

Ferromanganese crusts on Central, North-western Pacific and Atlantic clearly indicate multiphase formation processes. They occur on hard-rock substrates in the top parts of conical seamounts, on the flat-topped seamounts (guyots) and on the abyssal hills at the water depth of 400 to over 6000 m. They form encrusting layers mainly on the basaltic surfaces, but also breccias and gravellite forms composed from continuous parallel macrolayers. Crust form pavements of varying thicknesses and high physico-mechanical consistency degree.

The thickness varies from 0.1—0.2 up to 15—20 cm and is directly related to the seafloor relief and depth. The thickest one have been recorded between 800—1200 m and thinnest in 1200—2500 m, with some minor local variations. Below 2500 m thickness is decreasing. The crust boundaries with the substrate are sharp. They are enriched in metals mainly in the few centimeters upper layers (usually 2—8 cm) (Fig. 4). Crusts found locally, within the active volcanic cones, show low Co contents <0.1 %. Active volcanos usually are not covered by crusts.

Deposits are showing great spatial dimension variability and metal contents. The most important ore parameter of ferromanganese crusts are minimum cobalt content = 0,4 % and thickness >2.5 cm.

The highest occurrence of Fe-Mn crusts has been recorded in the seamounts and volcano-tectonic rises in the north-western part of Pacific, Southern Atlantic and Indian Ocean. Those crust formations have been associated with volcanic activity zones showing highly varied relief mainly in the depths of more than 1000 m. Ferromanganese crusts on the volcano-tectonic rises region in the Atlantic (New England Seamounts, Rio Grande and Sierra Leone) are directly related to the past volcanic activity occurring in the last 10—15 million years. The distinctive feature of mentioned seafloor elevations and guyots is, in general, the volcanic bedrock sometimes covered with limestone. Flat, slightly undulating peak surfaces and sediment-free terraces favor their formation, often covered by foraminiferous sands and surrounded by barrier reefs. Guyots and conical seamounts slopes are characterized by steep flanks with 15—20° range and basalt outcrops. Basalt weathering products occurring on the outer-rim terraces are breccias, gravellites and sands. The average depth of the guyot summits is about 1500 m bsl, with a abyssal plain base at about 5000—5700 m bsl. The crystalline basement is represented mainly by tholeiitic basalts or sub-alkali (olivine) basalts of Cretaceous to Miocene age. Changes in the crusts isotope ratios are an important indicator of the last 60 million years climate fluctuations (Halbach et al. 1982; Herzig et al. 2000; Kotliński 2001; Andreev, Gramberg 2002; Kotliński 2008).

Ferromanganese crusts show high concentrations of Co (0.4—1.0 %) and Mn (25—30 %), with low Ni (0.6 %) and Cu (0.2 %) contents. Given high concentration of cobalt

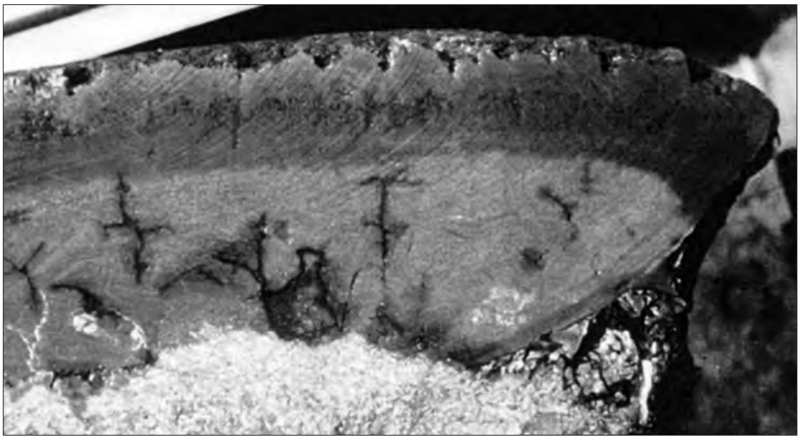

Fig. 4. Cross section of cobalt-rich ferromanganese crust from CCFZ (photo: M. Zadomov 2001)

in the crusts, two main types of crusts have been distinguished: multilayered (more than 6 cm in thickness) with a lower concentration of Co = 0.5—0.8 % (Wake, Ogasawara, Magellan seamounts in the Pacific) and single-layered (3 to 6 cm thick) with a higher Co concentration ≥ 0.8 % (Necker seamounts, a volcanic-tectonic chain of Lain and Hawaii).

Layered formation of the crusts is a distinctive feature of these encrustation, and applies to all recognized locations. The most prospective crusts are these with thicknesses ranging from 3 to 6 cm with cobalt content above 0.45 %. The main mineral phase of Co, Mn and Ni-reached crust is vernadite. At higher Fe content, increase in Ti, Mo, REE and PGE content has been recorded. The content of minor components is lesser and shows broad spectrum.

Taking into consideration general dependencies of the individual generation of crust formation, the following disclosed and recognized resource areas in the Magellan Seamounts area (Pacific) should be considered a foreground to conduct prospecting: Fedorov (MŻ-35), Alba (MA-15), Gramberg (MŻ-36), Gelendżik (MŻ-37), Butakov (MŻ-39), Govorov (MA-08), where prospective resources are estimated at about 80 million Mg of dry minerals (for each), and the total resources estimated to be around 300—400 million Mg (Fig. 2).

The most prospective areas in the Atlantic (Rio Grande, Walvis Ridge — Fig. 2) are poorer than in the Pacific. The crust occurs in the Atlantic at depths 1500—3500 m with contents: Mn (15—22 %), Co (0.55—0.60 %), Ni (0.45—0.5 % wt.) and small amounts of Mo, Pt i REE (Halbach et al. 1982; Halbach et al. 1984; Kotliński 2001; Andreev, Gramberg 2002; Hein 2006; Kotliński 2008; Hein 2010; Kotliński 2011).

The compilation of average concentration of rare earth elements and yttrium (REY) in oxide ferromanganese deposits (Tab. 1) shows that ferromanganese crusts in the Indian Ocean and the North Pacific have the highest content of REY. Polymetallic nodules contain moderate concentration of REY while these concentrations depend on nodule type. REY are most abundant in hydrogenetic nodules (Kotliński et al. 1997) while diagenetic contain less REY, what explains their low concentration in the Basin of Peru, where the second type of the nodules dominates (von Stackelberg 2000). While many land-based-mines are now extracting REE (eg. Mines Bayan Obo in China,

Table 1. **Mean REY (rare earths + yttrium) composition of cobalt-rich ferromanganese crusts and polymetallic nodules in selected areas**

Element	Ferromanganese crusts					Polymetallic nodules		
	Atlantic	Indian Ocean	PCZ *	N Pacific	S Pacific	CCFZ	Peru Basin	Indian Ocean
	Mean content [ppm]							
La	272	290	339	320	204	108	68	128
Ce	1392	1469	1322	1360	818	255	110	452
Pr	63.8	66.2	61.3	61.2	40.8	32	14.1	33.0
Nd	243	259	258	275	184	135	63	144
Sm	55.5	60.8	51.5	56.8	38.1	32.7	14.0	32.1
Eu	11.5	12.5	12.5	13.7	17.5	7.83	3.87	7.78
Gd	57.9	67.2	56.2	66.3	43.9	31.0	15.6	31.0
Tb	9.17	9.99	8.79	9.55	5.98	4.78	2.52	5.00
Dy	47.1	55.6	60.0	56.0	40.7	27.5	15.8	26.2
Ho	9.61	10.60	10.90	10.80	8.45	5.12	3.42	4.87
Er	28.0	29.3	31.0	31.3	26.5	14.1	9.8	12.4
Tm	3.91	4.03	4.55	4.26	3.60	2.02	1.49	2.00
Yb	23.9	24.8	28.5	28.3	21.9	13.1	10.3	11.6
Lu	3.74	4.05	4.29	4.02	3.33	1.95	1.61	1.92
Y	181	178	221	190	177	92	69	—
Sc	16.40	12.50	6.55	11.1	9.29	11.00	7.58	—
ΣREY	2418.53	2553.57	2476.08	2498.33	1643.05	773.1	410.09	891.87

* Pacific Crust Zone or Pacific Prime Zone — central and western equatorial Pacific (from equator to 20°N latitude). Source: Hein, Koschinsky 2013; modified

Mountain Pass USA) as the primary ore, REE from the oceanic deposits (mainly ferromanganese crusts) would be extracted as a byproduct on a par with main metals (Mn, Ni, Cu, Co) (Hein et al. 2013; Messari, Ruberti 2013).

Polymetallic sulphides (seafloor massive sulphides — SMS)

Prospective polymetallic sulphides deposits occur in the rift valleys of mid-ocean ridges in the zones with a varied rate of oceanic crust accretion (Pacific, Atlantic, and Indian Ocean). In the Pacific, the polymetallic sulphides occur also in the volcanic arcs and marginal basins ranging depth from 1500 to 3500 m. They form isolated hydrothermal vents, cones and rises of varying sizes.

Mineral resources in SMS range from a few hundred to a million Mgs of sulphide ore, with extremely diverse contents of major metals (Zn, Cu, Pb) and often enriched in Ag and Au. Enrichments zones have several tens of meters. Deposits are solid, massive and showing great hardness. Due to the high concentrations of critical metals and promising results of the application of effective methods of resources identification and documentation, as well as new mining technologies, this type of deposits are highly perspective (Halbach et al. 1982; Halbach et al. 1984; Kotliński 2001; Andreev, Gramberg 2002; Cherkashov et al. 2004; Andreev, Cherkashov 2005; Hein 2006; Kotliński 2008; Hein 2010; Kotliński 2011).

SMS occurrence regions are associated with the spreading axes of the mid-ocean ridges and volcanic arcs in the marginal basins. Ridges characterized by the presence of asymmetric faults limiting rift valleys, are distinguished by intensive hydrothermal and exhalation processes, concentrated both in the rift axis and on the slopes of the valleys.

SMS deposits are formed in the active magmatic centers as a result of the interaction of the cold ambient ocean waters with high-temperature hydrothermal fluids and oceanic basalts. In the conditions of high tectonic activity, faults and crevices allow infiltration of the ocean waters, then heating and forming a mixture with juvenile steam and causing finally selective extraction of elements from basaltic magmas.

The occurrence of SMS is regionally differentiated. The greatest number of potential resource areas have been located in the Pacific (388), the Atlantic (71), Indian Ocean (52), Mediterranean Sea (16) and the Arctic Ocean (10), with only 10 % locations recognized (Fig. 2) (Kotliński 2001; Hein 2006; Kotliński 2008; Hein 2010; Kotliński 2011; Zawadzki, Kotliński 2011; Zawadzki 2013).

In the Atlantic Ocean the highest concentration of sea-floor massive sulphides occur between transoceanic fracture zone Pico and Fifteen-Twenty, Kurchatov, Lucky Strike, Oceanographer, Broken Spur, TAG, Snake Pit and Logatchev (Fig. 2). They are low-spreading ridges (< 3 cm/year). Sulphides form domes ranging up to 70 m in height, with a base diameter up to several hundred meters.

The most prospective areas of exploration of the polymetallic sulphides are nodal basins, often forming triple junctions at the intersection of transforming faults and the rift. They are characterized by the occurrence of a nonadjacent extensive structures and numerous cracks and oblique-slip faults. Accumulation of sulphides occurring in the Mid-Atlantic Ridge (MAR) and East-Pacific Rise (EPR) is characterized by extremely diverse content of metals and their high concentrations. SMS are characterized by varying amounts of zinc, copper, silver and gold.

One of the most currently recognized areas is Solwara 1 — a mine site located in the Bismarck Sea (Pacific), occurring at about 1600 m bsl in the Exclusive Economic Zone of Papua — New Guinea (Fig. 2.; Nautilus Minerals Inc.) (Cronan 2000; Cherkashov et al.; 2004; Rona 2004; Andreev, Cherkashov 2005; Hein 2006; Kotliński 2008; Kotliński 2011; Zawadzki, Kotliński 2011).

Metallogenic potential of eupelagic sediments

As shown by Kato et al. (2011), who studied more than 2,000 deep-ocean ooze samples from 78 stations of the Pacific Ocean seafloor, some areas may be considered prospective in terms of acquisition of certain critical metals (REY). Among others, two regions are significantly enriched in REY: the eastern South and central North Pacific in the eastern South Pacific (5°—20° S, 90°—150° W) and the North Pacific east and west of the Hawaiian Islands (3°—20° N, 130° W—170° E). ΣREY varied 1,000 — 2,230 ppm (200—430 ppm total HREE) and 400—1,000 ppm (ΣHREE = 70—180 ppm) respectively. Oozes REY contents are comparable to or greater than those of the southern China.

Geochemical analysis of 137 samples of the siliceous-clayey silts from IOM H11 Fe-Mn nodule deposit (eastern part of the Clarion — Clipperton nodule field) has shown that total REE content temporally should not be considered as economical important. Total content of REE is low and ranges from 199,99 ppm to 616,56 ppm with an average of 288,81 ppm, while the amount of heavy rare earths (ΣHREE) ranges from 214,22 ppm to 54.27 ppm, with a mean value of 83,36 ppm (Zawadzki et al. 2014).

International legal development aspects of the oceanic polymetallic mineral deposits

Intensified geological-exploration research confirm the significant increase in interest in the development of deep-ocean mineral deposits, which constitute alternative source of critical metals. Currently, the ISA has entered into 15-year exploration contracts for polymetallic nodules, polymetallic sulphides and cobalt-rich ferromanganese crusts with twenty-one contractors (Tab. 2; state for April 2015). Fourteen of these contracts cover exploration for polymetallic nodules in the Clarion-Clipperton Fracture Zone (13) and Central Indian Ocean Basin (1). There are four contracts for polymetallic sulphides exploration in the South West Indian Ridge, Central Indian Ridge and the Mid-Atlantic Ridge and three contracts for the exploration for cobalt-rich crusts in the Western Pacific Ocean.

The number of potential contractors will undoubtedly grow in the next few years, leading to a significant «nationalization» of the ocean floor and its fragmentation into sectors. This process is particularly evident in the group of rapidly developing countries (China, India, Brazil), destroying the relative geopolitical balance still existing in the process of the ocean floor division.

Present-day limitations in the development of deep-ocean mining of polymetallic deposits are primarily associated with: (1) the complex legal and administrative aspects of the geological and mining works, as well as recovery process itself within the different territorial units of marine waters; (2) absence of precise geological boundaries between the selected basins (as well as the other geomorphological features of the seafloor), or discrepancies in the position assessment of these boundaries in relation to national borders; (3) continuing absence of low-cost efficient technologies related to the exploitation of mineral deposits located at significant depths, their initial extraction and, in many cases, considerable distance from the land-based processing plants; (4) low market prices and significant fluctuations in the price of certain metals predominating in the ore (main eg. are Fe and Mn); (5) discovery and development of new land-based resources, operated using cheaper and less complex technologies (recycling, urban mining, mining in the polar regions); (6) uncertainty related to the divergence of the environmental impact assessments of deep-ocean mining (eg. the release of sediment plums containing heavy metals, acoustic degradation of fisheries, destruction of fragile ecosystems of black and white smokers, the issue of ore dewatering etc.) (Cook 1974; Clark, Clark 1986; Earney 2005; Littleboy, Boughen 2007; Tsamenyi i in. 2007; Parr 2008; Rona 2008; Kotliński 2011; Rosenbaum 2011; Hein, Petersen, 2013).

Geological and exploratory activities, aiming at identification and development of oceanic polymetallic mineral deposits found in the area of «open seas», are protected by the relevant international legal regulations. ISA, the international law body, organizes and controls activities in the so-called «Area», particularly with a view to administer the resources of the Area.

Currently, the participants in the United Nations Convention on the Law of the Sea (UNCLOS) are 165 countries and the European Union (ISA 2014). In accordance with UNCLOS Resolution II, «Pioneering Investors» have the exclusive right to research on the assigned and registered areas of the ocean floor. The contractor status guarantees the exclusive right to conduct exploration and obtain a license for the industrial development of polymetallic mineral deposits.

The degree of recognition of prospective mining areas is extremely varied. Some of them are recognized at «Prospection» stage and part in «General» or «Detailed Exploration» phase. In addition to mining areas already registered, many countries are in

Table 2. **List of contractors who signed agreement with ISA for exploration of deep-ocean mineral resources in the open sea, according to United Nations UNCLOS 1982**

Id	Contractor	Contract start	Sponsoring State	Location	Contract End
Polymetallic nodules					
1	Interoceanmetal Joint Organization (IOM)	29.03.2001	Bulgaria, Cuba, Czech Republic, Poland, Russian Federation and Slovakia	Clarion-Clipperton Fracture Zone (CCFZ)	28.03.2016
2	Yuzhmorgeologiya	29.03.2001	Russian Federation	CCFZ	28.03.2016
3	Government of the Republic of Korea	27.04.2001	Korea	CCFZ	26.04.2016
4	China Ocean Mineral Resources Research and Development Association (COMRA)	22.05.2001	China	CCFZ	21.05.2016
5	Deep Ocean Resources Development Co. Ltd. (DORD)	20.06.2001	Japan	CCFZ	19.06.2016
6	L'Institut francais de Recherche pour l'Exploitation de la mer (IFREMER)	20.06.2001	France	CCFZ	19.06.2016
7	Government of India (GOI)	25.03.2002	India	Mid-Indian Ocean Basin	24.03.2017
8	Federal Institute for Geosciences and Natural Resources of Germany	19.07.2006	Germany	CCFZ	18.07.2021
9	Nauru Ocean Resources Inc.	22.07.2011	Nauru	CCFZ	21.07.2026
10	Tonga Offshore Mining Limited	11.01.2012	Tonga	CCFZ	10.01.2027
11	Marawa Research and Exploration Ltd.	19.01.2015	Kiribati	CCFZ	18.01.2030
12	G TEC Sea Mineral Resources NV	14.01.2013	Belgium	CCFZ	13.01.2028
13	UK Seabed Resources Ltd.	08.02.2013	United Kingdom of Great Britain and Northern Ireland	CCFZ	07.02.2028
14	Ocean Mineral Singapore PTE Ltd	22.01.2015	Singapore	CCFZ	21.01.2030
Cobalt-rich ferromanganese crusts					
15	China Ocean Mineral Resources Research and Development Association (COMRA)	29.04.2014	China	Western Pacific Ocean	28.04.2029
16	Japan Oil, Gas and Metals National Corporation (JOGMEC)	27.01.2014	Japan	Western Pacific Ocean	26.04.2029
17	Ministry of Natural Resources and Environment of the Russian Federation	10.03.2015	Russian Federation	Magellan Mountains, Pacific Ocean	09.03.2030

Table 2 (completed)

Polymetallic nodules					
Id	Contractor	Contract start	Sponsoring State	Location	Contract End
	Polymetallic sulphides (SMS)				
18	China Ocean Mineral Resources Research and Development Association (COMRA)	18.11.2011	Chiny	Southwestern Indian Ridge	17.11.2026
19	Government of the Russian Federation	29.10.2012	Russian Federation	Mid-Atlantic Ridge	28.10.2027
20	Government of the Republic of Korea (CORDI)	24.06.2014	Korea	Central Indian Ridge	23.06.2029
21	L'Institut francais de Recherche pour l'Exploitation de la mer (IFREMER)	18.11.2014	France	Mid-Atlantic Ridge	17.11.2029

Source: ISA 2014, www.isa.org.jm, slightly modified (access: April 2015).

the process of preparing applications for new areas. The distinctive feature of the current stage of exploration of deep-ocean mineral deposits is widespread use of new unified methods, techniques and technologies in exploration and documentation, characterized by complexity and high efficiency.

Global economic problems resulting from the scarcity of many raw materials and the need access for alternative sources of metals, give many opportunities of integrated cooperation with groups of countries interested in new mineral deposits. Therefore, undertaken activities should significantly expand the areas of international cooperation in the field of geological research and documentation of metallic resources.

Metal resources in prospective recognized Fe-Mn oxide deposits and sulphides may lead to significant future changes in supply and demand of strategic metals in the global markets. The growth rate of demand for metals is showing an upward trend nowadays. The most important factor in the economic assessment of the value of polymetallic depositsis relatively higher metal content compared to the currently exploited land deposits and their prognostic resources. Regardless of the estimated resources of land deposits, high content and wide range of metals in deep-ocean mineral deposits guarantee their greater economic stability in the future.

Several research results in marine geology and mineral resources of the World Ocean confirm many hypotheses proposed during scientific career by the Academician of the National Academy of Sciences of Ukraine (NAN Ukraine) prof. Evgeni Fiodorovich Shnyukov. One of them was to confirm and estimate great metallogenic potential of the oceans, according to initial international regulations, which were formally established years after. Successful studies and promising results obtained by many countries, regarding the importance and the identification state of the ocean mineral resources, confirm the pioneer ideas of NAN Academician E. F. Shnyukov initiated more than 50 years ago within the framework of the integrated international research programs.

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ПОТЕНЦИАЛ И СОВРЕМЕННЫЕ ПРОБЛЕМЫ ИЗУЧЕНИЯ ВОЗМОЖНЫХ ИСТОЧНИКОВ ПОЛИМЕТАЛЛОВ В ОКЕАНИЧЕСКИХ ОСАДКАХ

Статья представляет экономические возможности добычи стратегических металлов из океанических полиметаллических руд и выделяет геополитические проблеммы, связанные с разделом морского дна.

К числу наиболее важных океанических металлоносных осадков относятся: (1) россыпи тяжелых металлов; (2) полиметаллические конкреции; (3) обогащенные кобальтом железомарганцевые корки; (4) донные рудные залежи сульфидов; (5) металлосодержащие илы и глины. Некоторые из них рассмотриваются как альтернативные ресурсы стратегических металлов для высоких и зеленых технологий. Их широкое распространение, ресурсы и источники — отражение геодинамической эволюции океана.

Авторы также обсуждают международное регулирование в области исследования, разведки, эксплуатации океанических месторождений полезных ископаемых, включая наиболее перспективные площади, добычи по морскому дну в соответствии с Конвенцией Организации Объединенных Наций по морскому праву (КМП 1982).

Ключевые слова: *полиметаллические конкреции, кобальт железомарганцевых корки, отложения сульфидов, металлосодержащие глины, экономическая геология.*

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ПОТЕНЦІАЛ І СУЧАСНІ ПРОБЛЕМИ ДОСЛІДЖЕННЯ МОЖЛИВИХ ДЖЕРЕЛ ПОЛІМЕТАЛІВ В ОКЕАНІЧНИХ ОСАДАХ

В статті представлено економічні можливості видобутку стратегічних металів з океанічних поліметалічних руд і виділено геополітичні проблеми, пов'язані з розділом морського дна.

До числа найбільш важливих океанічних металоносних осадів відносяться: (1) розсипи важких металів; (2) поліметалеві конкреції; (3) збагачені кобальтом залізо-манганові кірки; (4) донні рудні поклади сульфідів; (5) металовмісні мули і глини. Деякі з них розглядаються як альтернативні ресурси стратегічних металів для високих і зелених технологій. Їх значне поширення, ресурси й джерела — відбиття геодинамічної еволюції океану.

Також обговорено міжнародне регулювання в області дослідження, розвідки, експлуатації океанічних родовищ корисних копалин, включаючи найбільш перспективні площі видобутку з морського дна відповідно до Конвенції Організації Об'єднаних Націй з морського права (КМП 1982).

Ключові слова: *поліметалеві конкреції, кобальт залізоманганові кірки, поклади сульфідів, металовмісні глини, економічна геологія.*